The Space Factor

– Fundamental and applied research benefiting Europe's citizens and economy

M. Heppener
ISS Utilisation and Microgravity Promotion Division,
ESA Directorate of Manned Spaceflight and Microgravity,
ESTEC, Noordwijk, The Netherlands

Although 'made in space' products are not expected to appear in the near-future, space is gaining interest as an area for industrial or applied R&D. ESA is supporting a growing number of projects involving non-space industries and other third parties. This article gives an overview of the potential of research in space to develop valuable applications on Earth.

Introduction
Some 20 years ago, the title of this article might have carried an additional letter: *The Space Factory.* In those days, it was believed that the microgravity environment in space had such high potential for developing new technologies and products that complete industrial plants would soon appear in the skies.

Since then, of course, these expectations have dimmed considerably, the main reason being the low number of flight opportunities and the high costs and long waiting times associated with performing experiments in space. It should not be forgotten that early projections predicted up to 60 Space Shuttle launches per year!

Reality has lagged behind those early expectations by almost a full order of magnitude. Nevertheless, progress has been made and, although 'made in space' products are not expected to appear on the market anytime soon, space as an area for industrial or applied research and development is gaining interest.

ESA is at the forefront of this development and is supporting a growing number of projects in which non-space industries, hospitals and other third parties are participating. This article gives an overview of the potential of research in space to develop valuable applications on Earth.

Basic research
In the past two decades, research in life and physical sciences in space has matured. The number of publications in international, peer-reviewed journals has almost doubled, both in number and quality (as measured by the 'impact factor'), as can be seen from Figure 1. These findings are confirmed by more recent surveys at national level in several European countries. In the last few years, publications on space experiments have even surpassed the average impact factor of publications in the respective disciplines.

Experiments are selected by independent, international peer reviews according to the most stringent, internationally accepted procedures and criteria. Presently, the success rate for proposals is of the order of 30%, a figure that is generally accepted to be the optimum in science reviews, ensuring high competition and scientific quality without discouraging proposers until they lose interest in applying.

Indeed, it is interesting to note that this competitive environment and the resulting high quality of the selected experiments attract newcomers and scientists of high reputation rather than deter them. A survey on proposals submitted in response to recent Announcements of Opportunity (AOs) shows that a third of scientists are participating for the first time in a space experiment. Currently, the database of interested scientists and industrial users encompasses more than 12 000 individuals in Europe.

Since 1998, almost 800 proposals have been received, of which 256 have been rated as Outstanding or (Highly) Recommended by the peers. In total, more than 1100 scientists are participating in these proposals directly, and several hundreds more are involved indirectly. Figure 2 gives a distribution per country of the scientists involved in these projects. Several non-ESA member states are included in this list, notably the US, Russia and Japan, plus several East European countries (Hungary, Bulgaria, Czech Republic, Lithuania, Poland and Romania). This demonstrates the global character of the research community.

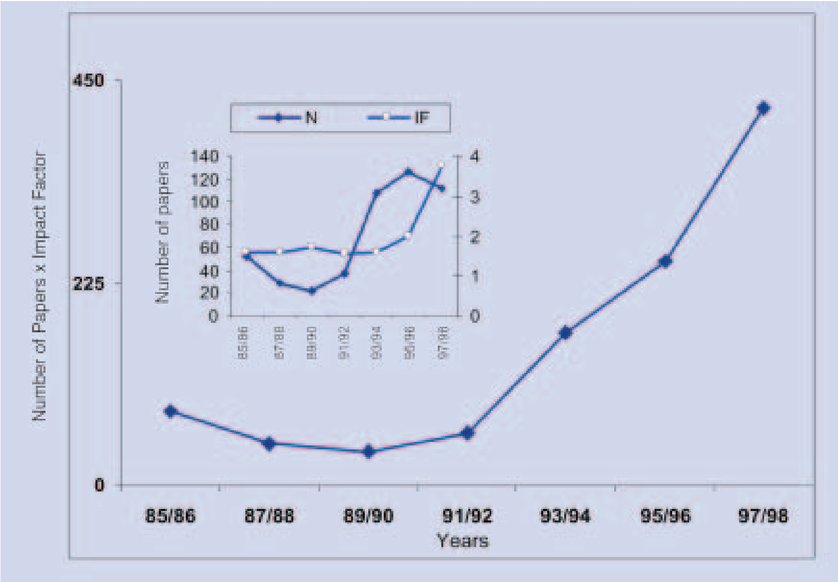

Figure 1. Increase in *quantity* and *quality* of publications in space-related European life sciences over the past few years. From a survey made in 1999

Applied research

In any scientific discipline, basic research is the starting point for progress. For that reason, basic research has received continuous support within life and physical sciences in space. Proposals of scientific excellence will generate new ideas in the pure sciences, that will, after gestation, find their way into novel practical applications.

A good example is the development of the laser. First predicted on theoretical grounds by Albert Einstein in 1917, the first real operational laser was not built until 1960. Nowadays, lasers are found in numerous appliances such as printers and CD players. From this perspective, it is surprising to see that several concrete ideas for applications are already emerging in life and physical sciences in space.

As instructed by the 1995 Ministerial Council, ESA has actively pursued applied research on the ISS. An important first step was the establishment of Topical Teams of scientists from academia and industrial R&D laboratories. These teams are promoting dialogue between the partners, identifying common interests and developing concrete suggestions for application-oriented research.

The second step consists of incorporating application-oriented research in ESA's AOs for Life and Physical Sciences. The first was issued in 1998. Important new elements were that the AOs:
- deal with basic and applied research,
- call for research programmes, rather than proposals for individual flight experiments,
- call for teams with a European dimension, rather than individual Principal Investigators,
- strongly welcome partners from non-space industries.

Since 1998, some 150 proposals for applied research have been received. As for basic research, these proposals have been reviewed by independent peers using basically the same criteria, but now including the element of 'application potential'. Again, the average success rate in this review ended up at about 30% – 43 projects have been approved (Table 1).

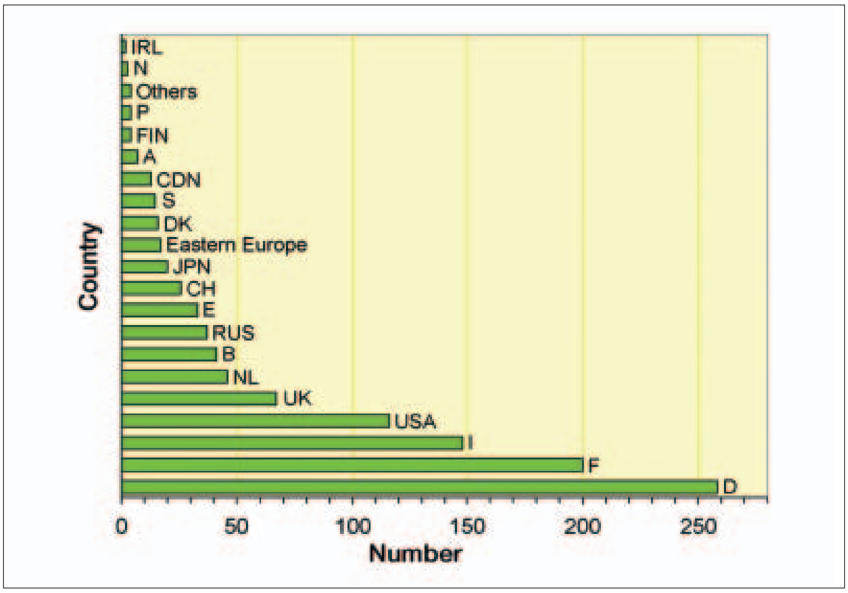

Figure 2. Distribution of the 1077 scientists involved in approved projects that form the scientific and industrial basis of ESA's life and physical sciences in space (ELIPS) programme

It is essential to recognise that all these 43 projects are run by trans-national teams. There is hardly any project in which participants from fewer than three European countries are involved. Also, as requested in the AO, the presence of researchers from industry is apparent. In total, 116 European companies are involved, among which there are some very large multinationals and a significant number of start-up companies and Small- and Medium-sized Enterprises.

As ESA does not fund the research activities of the industrial participants, they are committed to bring their own funding. Also, the funding for the non-industrial partners was limited. In particular, ESA provides funding to a fixed maximum amount determined by the application potential as determined by the peers. If there is no application potential, ESA's

Table 1. The 43 approved applied research projects.

AO Number	Name of Project	Discipline	Coordinator
AO-99-003	Modular space bioreactor for medically relevant organ-like structures	Biotechnology	Cogoli
AO-99-007	Investigations on soot concentration and primary particle sizes by advanced laser-induced incandescence.	Physical Sciences	Will
AO-99-010	Undercooling and demixing of Cu-Co alloys	Physical Sciences	Egry
AO-99-013	Vibration exercise as a countermeasure for muscular atrophy and bone loss	Life Sciences	Felsenberg
AO-99-021	Thermal transport phenomena in magnetic fluids under microgravity conditions	Physical Sciences	Odenbach
AO-99-022	Thermolab – high precision thermo-physical property data of liquid metals for modelling of industrial solidification processes	Physical Sciences	Fecht
AO-99-023	Non-equilibrium solidification, modelling for microstructure engineering of industrial alloys	Physical Sciences	Herlach
AO-99-026	Solidification morphologies of monotectic alloys	Physical Sciences	Ratke
AO-99-030	2d and 3d quantification of bone structure and its changes in microgravity condition by measures of complexity	Biotechnology	Gowin
AO-99-031	Microstructure formation in casting of technical alloys under diffusive and magnetically controlled convective conditions	Physical Sciences	G. Mueller
AO-99-035	Crystallisation of CdTe and related compound	Physical Sciences	Fiederle
AO-99-045	Study of an imposed electrostatic field on pool boiling heat transfer and fluids management	Physical Sciences	Grassi
AO-99-052	Fundamental and Applied Studies of Emulsion Stability (FASES)	Physical Sciences	Passerone
AO-99-058	Development and application of a miniaturised respiratory sensor system	Life Sciences	Fasoulas
AO-99-075	Development of advanced foams under microgravity	Physical Sciences	Banhart
AO-99-081	Long term microgravity: a model for investigating mechanisms of heart disease with new portable equipment	Life Sciences	Norsk
AO-99-083	Chemo hydrodynamic pattern formation at interfaces	Physical Sciences	Mueller
AO-99-085	Laminar diffusion flames representatives of fires in microgravity environment, combustion properties of materials for space applications	Physical Sciences	Joulain
AO-99-091	Eristo-osteoporosis	Biotechnology	Braak
MED-024	Eristo-osteoporosis (funding added to above contract)	Biotechnology	Braak
AO-99-094	Combustion properties of partially premixed spray systems in fields of droplet and spray combustion	Physical Sciences	Eigenbrod
AO-99-098	Perception of gravity, signal transduction and graviresponse in higher plants by innovative genomic technologies	Biotechnology	Palme
AO-99-101	Study and modelling of nucleation and phase selection phenomena in under-cooled melts: application to magnetic and refractory alloys of industrial relevance	Physical Sciences	Loeser
AO-99-108	Hydrodynamics of wet foams	Physical Sciences	Langevin
AO-99-110	CIMEX: Convection and Interfacial Mass Exchange	Physical Sciences	Legros
AO-99-111	Diffusion and SORET coefficients measurements for improvement of oil recovery	Physical Sciences	Legros
AO-99-114	Metastable solidification of composites: novel peritectic structures and in-situ composites	Physical Sciences	Herlach
AO-99-117	Columnar-Equiaxed Transition in Solidification processing (Cetsol)	Physical Sciences	Billia
AO-99-121	Ballistic and holographic 3-D high-resolution imaging of bone	Biotechnology	Hoffmann
AO-99-122	Bone metabolic studies in a combined perfusion and loading chamber	Biotechnology	Jones
LSS-003	Investigation of developmental pathways leading to bone formation and bone momeostasis by genetic dissection and functional analysis of osteoprotegerin in a transgenic fish model on Earth and microgravity environment	Biotechnology	Goerlich
LSS-006	Vascular endothelial cells in microgravity: gene expression, cellular energy metabolism and differentation	Biotechnology	Bradamante
LSS-015	A total converting and biosafe liquefaction compartment for MELISSA	Biotechnology	Verstraete
LSS-017	Closed-habitat environmental control sensors	Biotechnology	Boarino
LSS-018	Molecular tools for monitoring and control of (pathogenic) bacteria in advanced	Biotechnology	Krooneman
LSS-019	Biological air filter for air quality control of life-support systems in manned spacecraft and other closed environments	Biotechnology	Van der Waarde
LSS-034	A Biosensor to monitor radiation-induced DNA damage on the ISS: risk assessment for astronauts	Biotechnology	Walmsley
MED-007	A novel system for in-vitro detection of gravity effects on primary haemostasi	Life Sciences	De Marco
MED-023	Echography doppler assisted by robotic arm (EDRA)	Life Sciences	Arbeille
MED-027	Effects of simulated and actual microgravity on muscle function during explosive efforts	Life Sciences	DiPrampero
MED-028	Microgravity effects on human skeletal muscle function investigated by surface EMG and mechanomyogram	Life Sciences	Merletti
MED-030	Resistance training using flywheel technology for crew stationed in space	Life Sciences	Tesch
MED-031	Airway nitric oxide in microgravity	Life Sciences	Linnarsson

contribution is zero; for very high application potential, the ESA funding could be up to 300 kEuro/year.

The outcome of this arrangement is that ESA, industries and academic institutions each participate at approximately the same level in funding these projects (Fig. 3). The resulting scheme has therefore led effectively to the establishment of true Public-Private-Partnerships.

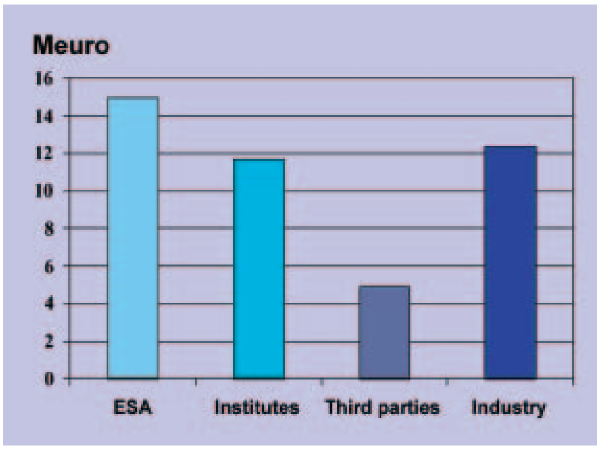

Figure 3. The distribution of the financial contributions to the costs of the application-oriented projects. The industries and the research institutes each contribute almost a third of the total project costs

Project details

The topics addressed in the 43 approved applied research projects cover a broad range (Fig. 4). An example is provided here for each of the Biotechnology, Health, Environment, (petro)Chemistry and (new) Materials categories.

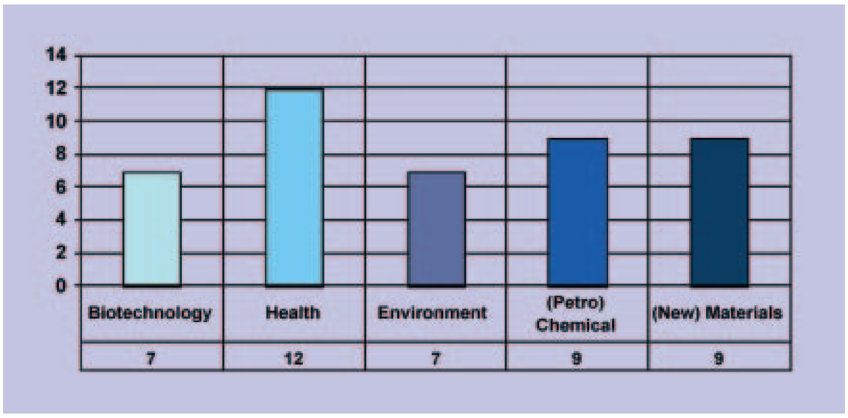

Figure 4. The topics addressed in the current set of 43 application-oriented research projects. Almost 125 European (non-space) industries are participating in these projects

Biotechnology: growing artificial tissues

Growing artificial human tissue for transplantation would be an answer to important medical problems. This would be true particularly if the starting material used cells directly from the patient. Such tissue would be free from the rejection currently encountered and would also be an essentially limitless supply.

Unfortunately, all attempts on Earth to make human cells grow *in vitro* in three dimensions seem to fail. Gravity is clearly a disturbing factor. Therefore, this project will attempt to culture human cells in a specifically designed bioreactor that can operate in weightlessness. The results of these experiments will help to unravel the cellular mechanisms underlying the growth of tissues in 3-D. The first trials will use a relatively simple tissue: cartilage. Cartilage transplants could help large numbers of people suffering from joint problems caused by sports accidents or diseases. Later, growth of more complicated tissues will be attempted.

In this example, two points should be stressed. First of all, the final objective of this project is not to grow tissues in space that will then be used for transplantation. Rather, it is hoped that the space experiments will lead to a method for growing functional tissues on Earth. Secondly, since clinical trials take a long time, this project, even if successful, will not lead to immediate breakthroughs in medical treatment.

Nevertheless, even if space experiments deliver only a few pieces of this complex puzzle, this project would already have proved its value.

Health: understanding, diagnosing and treating osteoporosis

One of the best-known effects of weightlessness on the human body is the loss of bone mass and structure. Once in space, astronauts can lose up to 20% of the calcium in their bones per year. This effect is not identical to, but closely resembles, the disease of osteoporosis. Obviously, this disease progresses much more slowly on Earth, but it has major consequences: it affects about 35% of women and 6% of men over 50 years of age.

Experiments in weightlessness are a good way to study the underlying mechanisms. In particular, advantages include the rapid availability of results and the fact that tests are done with otherwise completely healthy volunteers. Several projects are being supported by ESA; participants include university and hospital researchers, medical companies and developers of medical equipment.

Apart from real space experiments, tests are also being performed using bedrest studies, in which weightlessness is simulated by keeping volunteers in a 6º head-down tilt for extended periods. Recently, a record 90-day bedrest study involving 25 volunteers was organised by ESA, CNES and NASDA at the facilities of MEDES in Toulouse (Fig. 5).

The objectives of the research in this domain are threefold:

– understanding the fundamental cellular and physiological processes involved in bone mass and structure loss,

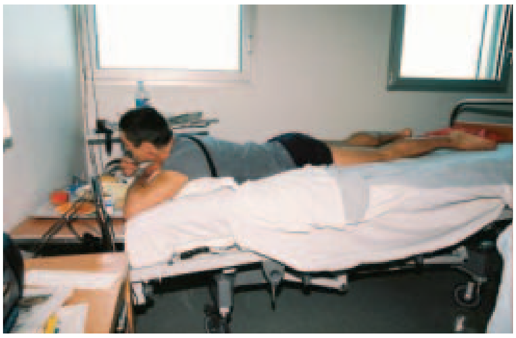

Figure 5. Dinner for one of the 25 volunteers in the 90-day bedrest study organised in 2001/2002 by ESA, CNES and NASDA

- developing new diagnostic tools for early recognition and monitoring of osteoporosis,
- testing new treatment methods, such as novel drugs or physical countermeasures.

Significant progress is being made in all areas. In particular, a novel exercise machine has been tested in bedrest studies and appears to be highly effective. Some new drugs show promise. Finally, a 3-D peripheral Quantitative Computed Tomography technique has been developed with good prospects for clinical application.

Environment: improving the efficiency of combustion

A 'classic' in space research is burning a candle in weightlessness. This simple experiment, in which the flame turns completely spherical and transparent blue, demonstrates the strong influence of gravity on the burning process. On Earth, the burning process gives rise to convection of the surrounding air, thus providing the traditional flame shape. This convection also means the burning is incomplete, while soot creates the yellow flame (Fig. 6)

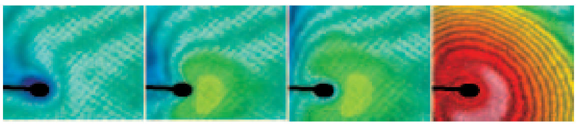

Figure 6. A typical example of a flame in weightlessness. The spherical shape and blue colour are due to the absence of gravity-induced convection

In spite of this apparently simple demonstration, combustion is a very complicated process. Numerous chemical reactions depend on local conditions such as concentrations and temperature, which in turn are determined by the flow velocities of the constituents. In space, the inherent flow velocity is negligible, but it is also possible to introduce artificial velocities using a controlled external airflow. These experiments can thus identify and quantify the influence of the various steps involved in the combustion process.

The results are of great interest for developing numerical models that predict how combustion proceeds under variable circumstances and geometries. Interested parties include companies who build power plants or car engines. They plan to use these improved computer models to optimise the efficiency or reduce the environmental loads of their designs.

(Petro)Chemical: increasing the yield of oil fields

Loosely related to the previous example is improving the accuracy of data used in analysing the contents of oil fields. Over geological timescales, the distribution of the constituents of an oil reservoir results from the dynamical equilibrium between:

- thermodiffusion driven by the geothermal gradient,
- diffusion driven by the concentration gradients,
- sedimentation driven by the hydrostatic pressure gradient (i.e. gravity).

From this it is clear that diffusion data are key to oil-reservoir numerical models developed by industry to optimise their drilling strategy. However, on Earth gravity prevents the measurement of the diffusive processes in multi-component systems, such as crude oil, in isolation.

In space, on the contrary, convection and stratification in multi-component mixtures is absent and these measurements can be made. The necessary equipment is in its final stages of development and the first measurements will be made during two missions later in 2002: the Soyuz Taxi mission of Frank De Winne to the International Space Station, and the Foton-M1 unmanned mission, both in October. If successful, more measurement campaigns will be planned. Some large oil companies are involved in this project, with several university groups.

(New) Materials: developing new casting techniques

In recent years, casting has developed from a rather straightforward activity to a very high-tech specialty. Today, very complicated moulds are used to produce, for example, entire engine blocks and other complicated structures. In order to fine-tune and guarantee the desired mechanical and other properties at each location in such a structure, detailed knowledge of the underlying solidification physics, and in particular the microstructure formation, is required.

Current computer models are not yet accurate enough to bridge the gap from the scientific microscopic length scale to macroscopic models useful to the casting industry. One of the main factors is the poor knowledge of the essential thermo-physical properties of liquid metals.

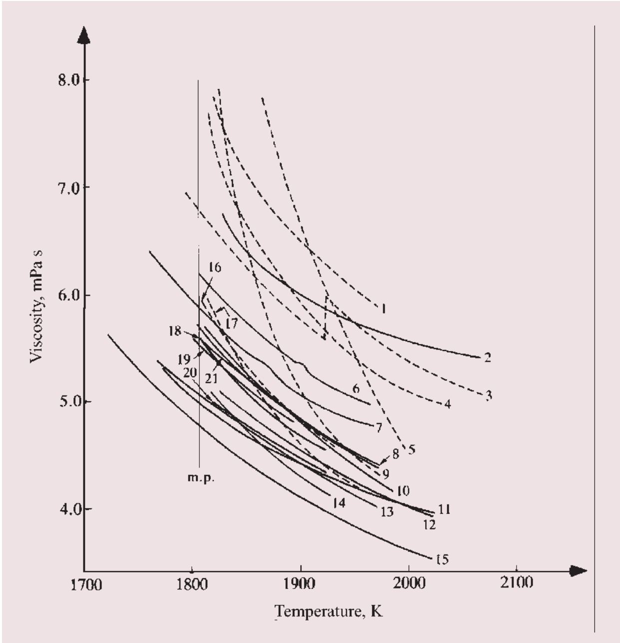

Figure 7. State-of-the art data on the viscosity coefficient of liquid iron

For example, even although molten iron is produced daily in enormous quantities, its very fundamental viscosity coefficient is known to an accuracy of only ±50%. Basically, only its order of magnitude is known (Fig. 7 provides an overview of relevant data). The reason for this low accuracy is that it is extremely difficult on Earth to obtain samples of pure molten iron. Owing to its high temperature and chemical aggressiveness, the walls of almost any container dissolve in the liquid metal and thus pollute it.

Under weightlessness, however, it is relatively simple to produce pure molten metal because, in principle, no container is necessary to hold the sample. With proper instrumentation, a sample can even be prepared in vacuum, and most of the important properties can be measured. The first trials are being planned for parabolic flight campaigns in the near future. For the longer term, specific equipment is being designed for the Space Station.

This theme is attracting very high interest from academic groups, and from a large number of companies. Indeed, a recent survey identified the need for this type of data from companies in the glass-making, enamelling, energy production, welding, foundry, casting, spray casting, secondary refining, alloy production and primary metal production businesses.

Future perspectives and conclusions

The above examples show that the emphasis of the applied research projects supported by ESA is not so much on production in space but on obtaining essential knowledge or data unavailable from Earth experiments. These projects are clearly in the pre-competitive R&D phase, but the significant interest from industry demonstrates their potential.

For the moment, the financial contribution from industry does not cover the launch costs, the development of the experimental facilities and, in particular, a share in the operational costs. It is to be expected, however, that as soon as the first successful experiments demonstrate the proof-of-concept, industries will be ready to increase their contribution to (partially) cover these aspects. Indeed, in some areas pathfinder projects are already being defined that could lead to a more commercial mode of operation.

Finally, the current set of 43 projects have inherent properties that should attract funding from programmes of the European Community:

– there is an identified benefit for economy or society
– the knowledge obtained in these projects will improve European competitiveness and technological knowledge base
– the topics correspond well to the thematic priorities identified in the Framework Programmes of the EC
– all the projects show strong participation from industry and academic institutes in several European companies (one of the prerequisites for obtaining EC funding).

EC funding has already been obtained for two examples mentioned above. In one osteoporosis project, ESA is an active partner and is contributing its own resources, complementing those from the EC. From recent contacts with participants in other projects, it is clear that is strong motivation for such collaboration. An ideal tool for this would be the Integrated Projects, a new funding instrument defined by the EC and which will be first used in the 6th Framework Programme to be launched in November 2002. In such Integrated Projects, ESA would take the responsibility for the space-related costs and aspects, whereas the EC funding would be used to develop the Earth applications. Preparations for such arrangements are under way.

In conclusion, it can be said that a new chapter in life and physical sciences research in space has begun. Although space factories are not expected to appear in the skies soon, the space factor will definitely start to deliver benefits to Earth in the foreseeable future.